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Geology

Structural geology of the Earth's interior*

(seismology/tectonics/mantle/convection)

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ABSTRACT Seismology is providing a more sharply focused picture of the Earth's internal structure that should lead to improved models of mantle dynamics. Lateral variations in seismic wave speeds have been documented in all major layers of the Earth external to its core, with horizontal scale lengths ranging from 10 to 10^4 km. These variations can be described in terms of three types of heterogeneity: compositional, aeolotropic, and thermobaric. All three types are represented in the lithosphere, but the properties of the deeper inhomogeneities remain hypothetical. It is argued that sublithospheric continental root structures are likely to involve compositional as well as thermobaric heterogeneities. The high-velocity anomalies characteristic of subduction zones—seismic evidence for detached and sinking thermal boundary layers—in some areas appear to extend below the seismicity cutoff and into the lower mantle or mesosphere. Mass exchange between the upper and lower mantles is implied, but the magnitude of the flux relative to the total mass flux involved in plate circulations is as yet unknown. Other observations, such as the vertical travel time anomalies seen in the western Pacific, may yield additional constraints on the flow geometries, but further documentation is necessary. Thermobaric heterogeneities associated with a thermal boundary layer at the base of the mantle could provide the explanation for some of the observations of heterogeneities in the deep mantle. The evidence for very small scale inhomogeneities (<50 km) in region D″ and for topography on the core–mantle interface motivate the speculation that there is a chemical boundary layer at this interface, as well as a thermal one.

The colors are chocolate, purple, lavender, and magenta, of many tones and shades. If it were not for this powerful coloring, which discloses every band and layer with emphasis, and each with a habit peculiar to itself, we could not venture to assert so much about them as we have done. For we have been reading geology from miles away from our rocks. But what are miles in this Brobdingnagian country!

—Capt. C. E. Dutton, describing the Paleozoic sequence at the head of the Grand Canyon (1).

The U.S. Geological Survey was founded by pioneers whose gaze was set on the grand scales of geology exposed in the American West. Confronted by a record laid starkly bare in these arid wastelands, they could not help but sense the movings within our planet. They vocalized their perceptions with bold new words: J. W. Powell gave us *diastrophism* to comprise the various processes of crustal deformation, which G. K. Gilbert (2) divided into *orogenic* (mountain-making) and *epierogenic* (continent-making); Dutton (3) defined *isostasy* to connote the tendency toward equality of total lithostatic loads, fully recognizing its control on vertical motions. The intervening century has witnessed considerable development of these concepts. From studies of Dutton's isostasy came the modern notions of lithosphere and asthenosphere. We now interpret the lithosphere to be a mechanically strong boundary layer that slides across the Earth's surface in huge rigid plates and the asthenosphere to be an underlying layer of convective flow. The great convulsions Gilbert called "orogenies" we now explain as the deformations caused when two plates collide, and we suspect that at least some epierogenic movements are isostatic responses to convectively induced variations in mantle temperatures (4).

Yet, even in this bright era of the plate paradigm, very little confidence can be placed in our understanding of the dynamical controls on surface tectonics, for their mechanisms are still only dimly perceived. Nearly every geophysicist postulates some form of thermal convection operating within the mantle, but many rudimentary constraints on the geometry of the flow are lacking. We do not know, for example, to what depth the mass circulation associated with plate motions persists. We cannot predict with much certainty or completeness the geographical distribution of ascending and descending currents nor, for that matter, even their statistics. We do know that the Earth is a chemically differentiated planet, and from the volcanoes seen on its surface we must conclude that some of the differentiation processes continue today, but we are only vaguely aware of what roles these processes have played in the planet's dynamical evolution. We are beginning to understand the complex history of the continental crust, but we can say almost nothing about the history of the mantle directly beneath this crust. In fact, much controversy clouds the discussions of continental deep structure.

There is little wonder, then, that our dynamical models are weak. We need a more sharply focused picture of Earth's internal structure. To give the dynamical theories some teeth, geophysicists will have to become structural geologists and map the features in the mantle and core that are manifestations of these dynamics.

How shall we do the structural geology of the Earth's interior? It is no easy task, for the phenomena to be studied lie beneath hundreds or even thousands of kilometers of rock, through which we have no direct access. The data must come, of course, from indirect observations near the surface. Studies of crustal structure and tectonics are providing critical facts about the underlying mantle, especially the studies of very large scale geological features; many of these reflect variations in upper mantle temperatures and compositions. Observations of the transient, noninertial responses of the surface to loading and unloading by large masses such as ice sheets and volcanoes, or by coseismic deformations, are yielding constraints on the mantle's constitutive parameters; these parameters control the balance of forces and are obviously critical to dynamical modeling. Petrological and geochemical analyses of the rocks brought up from the depths by volcanic action are demonstrating the existence of systematic, although puzzling, variations in both the major and minor elemental compositions of the mantle. Some of these chemical variations have evidently persisted in the mantle for eons and, thus, can contribute information about the dynamics averaged over time periods

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comparable to the age of the Earth. Work in all of these fields is proceeding at a vigorous pace, and hardly a day passes without the report of some new results.

But to map the details of interior structure necessary for understanding its dynamics, we must resort to geophysical techniques with higher resolutions: to studies of the Earth's gravity, electromagnetic, and elastic displacement fields. In this address I shall concentrate on seismological investigations of Earth structure—partially because it is the subject with which I am most familiar and also because I believe it to be the most promising source of information about the deep interior.

STRUCTURAL SEISMOLOGY

If the Earth were a perfect sphere whose pressure, temperature, and composition, and hence whose elastic parameters, varied only with distance from its center, then the travel times and amplitudes of the various seismic waves would depend only on the relative geometry of the source and receiver and not on their absolute coordinates. In fact, however, significant geographical differences in travel times and amplitudes have been observed, and analysis of them is revealing various structures within the mantle. For the surface and body waves sensitive to mantle properties, the spatial fluctuations of travel times are typically small, only rarely exceeding 10% in magnitude. Specific studies indicate that the wave speed variations responsible for these fluctuations are similarly small, at least for heterogeneities with scale lengths greater than 100 km or so. The weakness of lateral variations simplifies the analysis of the seismic data, especially travel time and eigenfrequency data, because variational principles can be used to construct approximate, but accurate, linear relationships between these particular data functionals and models of the heterogeneity.

Lateral variations in seismic wave speeds have been documented in all layers of the Earth external to its core, with horizontal scale lengths ranging from 10 to 10^4 km. In discussing this heterogeneity I will adopt the radial regionalization illustrated in Fig. 1. Although most of the terms have been standardized by historical usage, some of the nomenclature requires clarification. Following Daly (5), the silicate portion of the Earth is divided into three shells: a lithosphere, an asthenosphere, and a mesosphere. The lithosphere–asthenosphere boundary is taken to be the depth of compensation, here defined to be the level above which significant deviatoric stresses (say, >1 MPa or 10 bars) are sustained for geologically long periods of time (say, $>10^6$ yr) and below which material behaves as a viscous fluid with no significant strength (i.e., <1 MPa). This dynamical definition is more or less the classical one and does not necessarily identify the lithosphere with the region occupied by the coherent kinematical entities we call plates (for which I prefer and shall use Elsasser's term *tectosphere*), nor

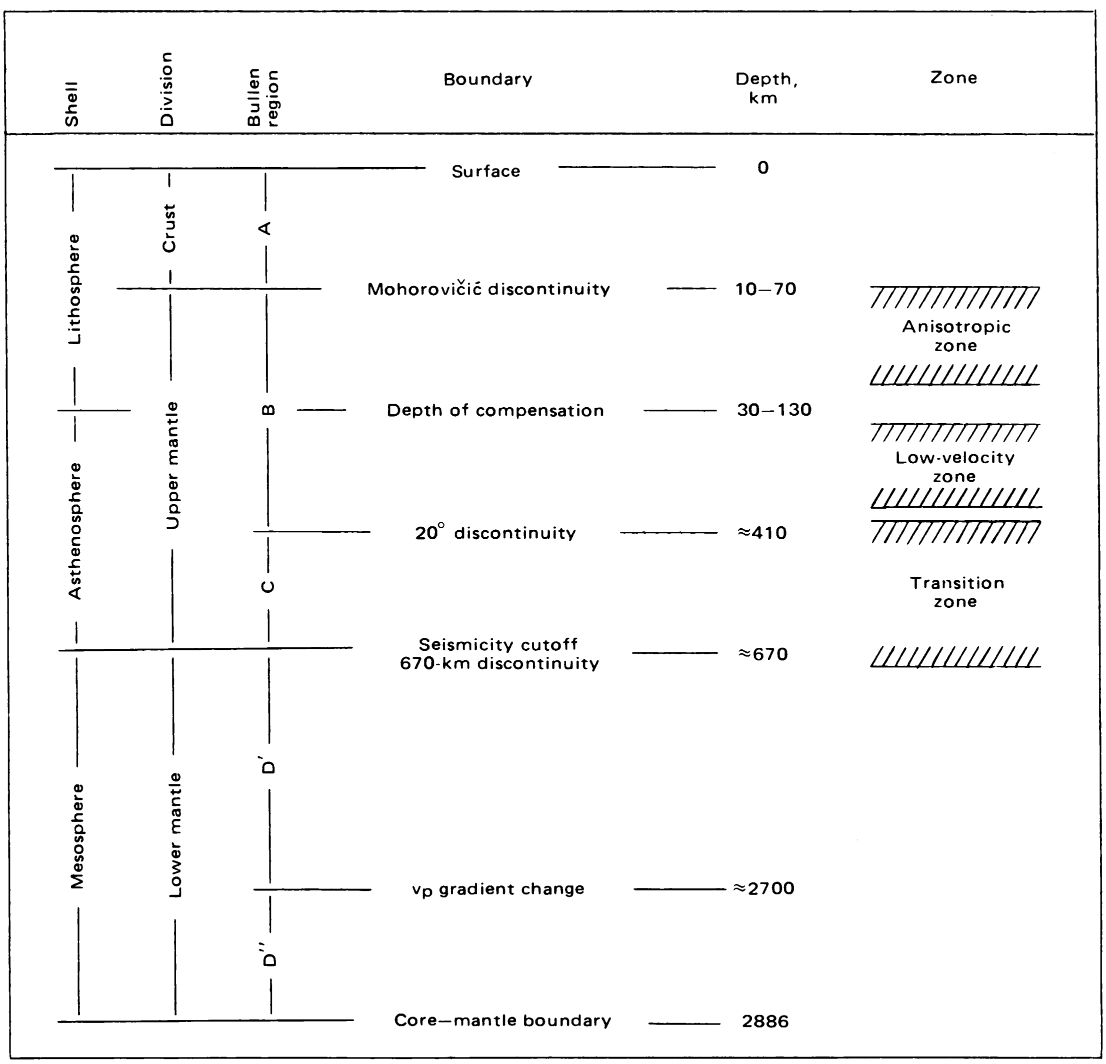

FIG. 1. Principal layers of the silicate Earth.

does it necessarily identify the asthenosphere with the Gutenberg low-velocity zone for shear waves.

Below the asthenosphere is the mesosphere, evisaged by Daly to be an inert, strong, lower mantle that does not participate in present-day tectonic processes. Isacks *et al.* (6) incorporated this concept into their model of lithospheric plate tectonics; they postulated that the convective circulation associated with plate motions is confined to a relatively thin asthenosphere whose base is marked by the abrupt termination of Benioff zone seismicity at depths of about 650–700 km. Most recent workers have abandoned the idea of a mechanically rigid mesosphere in favor of a convectively unstable lower mantle (7–14), but the question of whether or not there is much convective mixing between the upper and lower mantles remains the subject of controversy (discussed further below). Therefore, I will follow Isacks and others in defining the asthenosphere–mesosphere boundary by the seismicity cutoff, without necessarily accepting any inferences about the details of mantle circulation.

Fig. 1 also specifies the major seismological divisions of the silicate Earth—crust, upper mantle, lower mantle—as well as the finer regionalization of Bullen (15). The boundary between the upper mantle and the lower mantle is placed at the discontinuity in wave speeds observed near 670 km depth, which is also taken to be the base of Bullen's region C. This demarkation is somewhat shallower than Bullen's original definition based on the Jeffreys–Bullen velocity distribution (984 km), but it is concordant with more recent Earth models (16–18). Furthermore, it has the advantage of making this boundary essentially coincident with the seismicity cutoff (perhaps causally related to the existence of the 670-km discontinuity) and, hence, with the asthenosphere–mesosphere boundary.

In contrast with the mesosphere, neither the lithosphere nor the asthenosphere is specifically identified with any of the seismologically defined regions or zones. In some (and perhaps most) localities the subcrustal portions of the lithosphere appear to be distinguished by an anisotropic velocity structure (19–22), and the lithosphere–asthenosphere boundary may conform to the top of the Gutenberg low-velocity zone (both corresponding to constant, but possibly different, isotherms). At the present time, however, it seems wise not to generalize these relationships too strongly.

Region A Heterogeneity. Numerous local, regional, and global studies have established that the crust is inhomogeneous on essentially all scales sampled by seismic waves, from the hemispheric asymmetry of the continents and oceans to the small-scale heterogeneities responsible for high-frequency scattering (23, 24). Of course, these observations only confirm what is obvious to every structural geologist.

Region B Heterogeneity. All lines of evidence, seismological and otherwise, indicate that the uppermost mantle is also inhomogeneous across a wide spectrum of horizontal scales. As in the crust, high-frequency seismic waves are incoherently scattered by more-or-less randomly distributed bodies with characteristic dimensions of less than 30 km (24–26), although these scatterers could be more anisotropic than their crustal counterparts (22). Presumably much (but probably not all) of this inhomogeneity resides in the lithosphere, either frozen in during its formation or subsequently introduced by various magmatic and tectonic processes. Because their sizes are small compared to their depths, the exact mapping of these bodies will be difficult, and we may have to be contented with describing the gross statistical parameters of their distributions (e.g., root mean square amplitudes and correlation lengths).

For scale lengths greater than a few tens of kilometers, however, wave-speed maps of the near-surface heterogeneities can be obtained by the systematic inversion of relative travel time anomalies observed across dense seismic arrays (27–30). These techniques are still under development, with much current work aimed at increasing their three-dimensional resolving power. Preliminary reports indicate that the relative amplitudes of the primary waves are tractable model discriminants (30) and that gravity measurements can be successfully combined with travel time data in the formal inversion procedures (29). Already, important conclusions are being drawn. Aki (28) has surveyed the results, and he reports: "Significant small-scale ($20 \approx 50$ km) lateral inhomogeneity is observed everywhere to a depth of $100 \approx 150$ km, with the minimum estimate of root mean square fluctuation about 3%. The lithosphere–asthenosphere boundary seems to manifest itself as change in the roughness of anomaly pattern or in the trend of anomaly." He notes that there is a good correlation between the lithospheric anomalies and the surface geological features in active areas such as California, Hawaii, and Yellowstone but that the correlation is not as obvious in stable continental areas such as eastern Montana and Norway.

The manner in which region B anomalies correlate with surface geology is an important question for structural seismology because its answer can provide diagnostic information for interpretive modeling. Consider, for example, that tectospheric heterogeneities are defined to translate with the crust during normal plate motions and are therefore available to participate in long-term crustal evolution, whereas heterogeneities in the more mobile substrata are likely to participate only as transient disturbances or not at all. Actually, at the intermediate and large scales (>300 km), the correlation between long-term crustal history and the underlying wave speed variations in region B is remarkably good, especially in the continents. To illustrate some of these correlations I will use the crude tectonic map of Fig. 2, in which the oceanic crust is partitioned according to its age (or, more precisely, the square root of its age) and the continents are divided according to their Phanerozoic tectonic histories—i.e., by their generalized tectonic behaviors since ≈600 Myr ago.† Representative Rayleigh wave dispersion curves for the six tectonic regions are summarized in Fig. 3, and several kinds of shear wave travel time residuals are displayed as histograms in Figs. 4 and 5.

There is a general increase in Rayleigh wave phase velocities with increasing age of the oceanic crust and a corresponding decrease in shear wave travel times. This correlation is reasonably well explained by the growth, by conductive thermal decay, of a high-velocity low-attenuation boundary layer identified as the oceanic lithosphere (20, 36, 37, 40–42). Evidently this mantle layer, which seismologists term the "lid," attains a thickness of about 100 km in the oldest ocean basins, such as the western Pacific (41). Lid thicknesses derived by dispersion curve inversion (20, 36, 41) are in substantial agreement with other geophysical estimates of subcrustal lithospheric thicknesses, including the depth of Hawaiian seismicity (43), estimates based on loading response (44), and thermal models (45).

More puzzling, and more controversial in their interpretation, are the observations related to the large-scale lateral heterogeneity of continents and oceans. Both regional (33, 34) and

† This map, which has appeared elsewhere (31), was originally designed for the analysis of low-frequency eigenspectra and surface wave data to replace the schemes previously used by seismologists [e.g., plate IV of Umbgrove (32)]. The reader is cautioned, however, that many of the boundaries are approximate or interpretative, especially in the southern oceans, in continental regions whose true tectonic history has been obscured by Cenozoic platform cover, and in my necessarily subjective definition of what constitutes a "Phanerozoic orogenic zone or mobile belt."

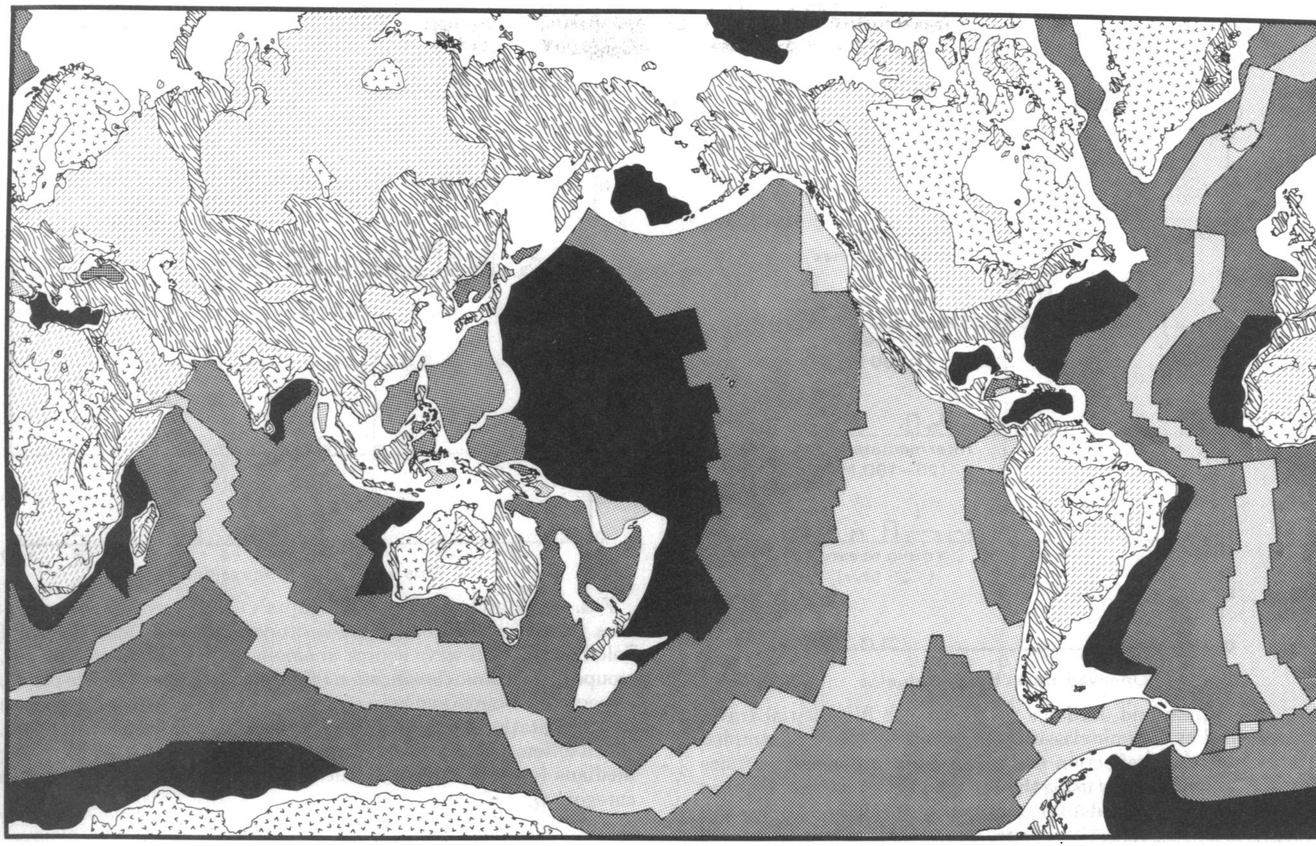

FIG. 2. Generalized tectonic map of the globe between 75°N and 70°S (Mercator projection). Oceanic crust is partitioned into three age regions: A, 0–25 Myr (□); B, 25–100 Myr (▩); and C, >100 Myr (■). Subaerial continental crust is partitioned into three regions based on Phanerozoic tectonic history: S, shields and platforms of exposed Archean and Proterozoic rocks with little or no Phanerozoic cover (□); P, platforms with relatively flat-lying, undisturbed Phanerozoic cover (□); and Q, orogenic zones or mobile belts with significant deformation or magmatic activity in the Phanerozoic (▧). White areas are regions of submerged continental or transitional crust, including continental margins, island arcs, and oceanic plateaus adjoining continental crust.

global (46, 47) surface wave studies have conclusively demonstrated that region B velocities are higher beneath the continents than beneath the oceans. The unanswered question is: How deeply do these variations extend? On this point, the lithospheric plate hypothesis, which identifies tectosphere with lithosphere, offers a specific, testable prediction: any structural variations globally coherent with the parameters of long-term (say, greater than 600 Myr) continental evolution should be confined to the lithosphere (say, above 130 km), because plate

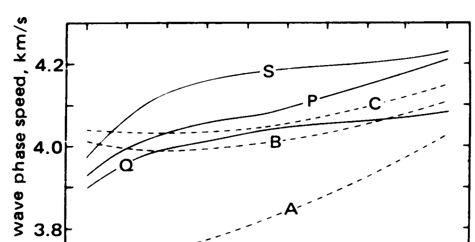

FIG. 3. Representative Rayleigh wave dispersion curves for the six tectonic regions of Fig. 2. Letters identify regions; phase velocities sample the following paths: S, Canadian Shield (33); P, Shiraz, Iran, to Jerusalem (34); Q, Charters Towers to Adelaide, Australia (35); C, Aleutian Is. to Afiamalu, Samoa (36); B, Gulf of California to Afiamalu, Samoa (36); A, Rivera Fracture Zone to Galapagos Is. (36). —, Continental; - - -, oceanic.

motions should continually rearrange sublithospheric heterogeneities with respect to surficial features. Furthermore, this model—at least its simple version—predicts that region B structural variations should be similar in old continents and old ocean basins, where the lithospheric thicknesses are presumably nearly equal (44).

Despite the merit of this model, its implications are difficult to reconcile with the seismic data now available. Consider the evidence in Fig. 4, where Sipkin and Jordan's (37) ScS_2-ScS travel time residuals‡ are grouped according to the crustal regionalization of Fig. 2. The median difference between one-way travel times for old oceans (category C of Fig. 2) and stable continents (categories S and P) is +3.0 s.§ About 1.5 s must be added to correct this value for known differences in crustal structures, so that, on the average, the actual one-way transit times of shear waves through the mantle differ by more than +4 s. The shear velocity variations required by this observation

‡ ScS is the shear phase reflected once from the core–mantle boundary; ScS_2 is reflected twice from the core and once from the surface. Because the near-source and near-receiver portions of their paths are similar, their travel time differences are insensitive to upper mantle velocity variations, except in the vicinity of the ScS_2 surface reflection points. Therefore, their differential travel times are useful for probing upper mantle heterogeneity in regions lacking seismic stations, such as ocean basins.

§ Okal and Anderson (48) have claimed that there is no significant difference in ScS_2-ScS times for these two regions, but a recent analysis (unpublished data) of a large set of multiple ScS phases digitally recorded by the High Gain Long Period Network confirms the results stated above.

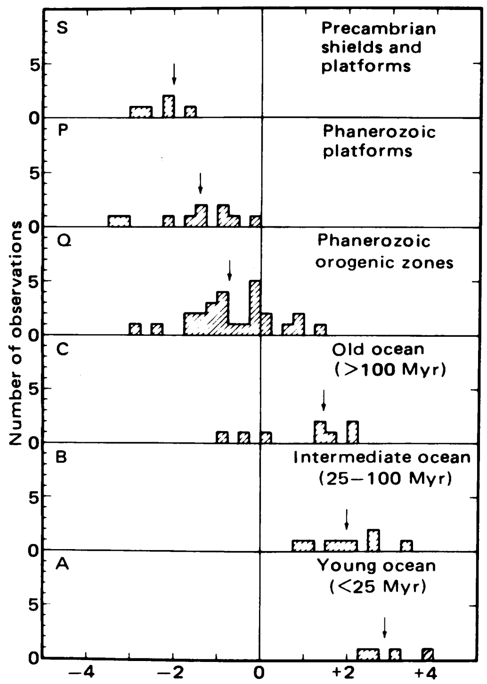

FIG. 4. Sipkin and Jordan's (37) ScS_2-ScS differential travel times, grouped by tectonic classification (Fig. 2) of the crust sampled at the ScS_2 surface reflection point. Residuals are observed times minus times computed by using the Jeffreys–Bullen tables (38); they are corrected for source depths, ellipticity, station elevations, and elevations of surface reflection points. All residuals have been divided by 2 to normalize them to one-way travel times. Arrows indicate medians for each category. Observations with surface reflection points on continental margins are included in category Q. Data were collected from the long-period instruments of the World Wide Standardized Seismographic Network (WWSSN).

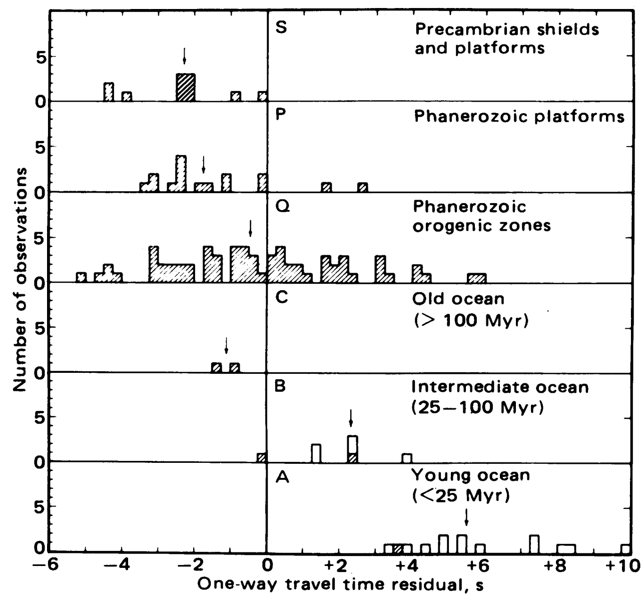

FIG. 5. Hatched bars are Sengupta's (39) S-wave station anomalies from deep-focus earthquakes; open bars are Duschenes and Solomon's (40) S-wave source anomalies for oceanic earthquakes, grouped by tectonic classification (Fig. 2) of receiver and source points, respectively. Source anomalies are relative to the Jeffreys–Bullen base line (38); station anomalies are relative to Sengupta's base line (39), which differs from the former by an average of −0.9 s. Arrows indicate medians for each category. Stations in island arcs are included in category Q.

cannot be accommodated in the lithosphere without violating surface wave constraints. Hence, the asthenosphere must be characterized by large-scale continent–ocean heterogeneity. One likely location for these variations is the Gutenberg low-velocity zone, which is weakly expressed or absent in most stable continental areas (33, 34) but is well-developed in the oceans, perhaps extending from the base of the lithosphere to depths on the order of 200 km (20, 36, 47). The surface wave data apparently preclude the confinement of the heterogeneity above this level, however, and some sort of deeper variations are implied. I have argued that continent–ocean heterogeneity probably extends throughout Bullen's region B and perhaps below it (49). This inference is concordant with Sacks and coworkers' (50, 51) interpretation of continental structure in South America and Alexander's (52) interpretation of the group and phase velocities of surface waves, but it remains controversial (48, 53, 54). Current work on higher mode dispersion (55–57) should resolve these questions.

The surface wave and travel time data also demonstrate the existence of intracontinental inhomogeneity in region B that is globally coherent with surface properties and tectonic history (34, 37). Continental areas that have acted as orogenic zones or mobile belts during the Phanerozoic (category Q of Fig. 2) tend to have lower shear velocities than do the more stable continental regions, and their velocity structures are more variable. Much of the category-Q variations seen in Figs. 4 and 5 are correlated with heat flow variations and magmatic activity, implying a thermal control. The two most positive (>+5 s) station anomalies in category Q of Fig. 5, for example, are sites in the magmatically active rift zones of Africa (Addis Ababa, Ethiopia, and Nairobi, Kenya); high values are also associated with station anomalies or ScS_2 surface reflection points in the Basin and Range and in eastern Australia, other areas of recent magmatism and high heat flow, whereas negative residuals occur in magmatically quiescent regions of lower heat flow, such as the southeastern United States and northeastern Siberia. These correlations have been recognized by many authors (e.g., refs. 34, 37, and 46) and have been attributed primarily to variations in or above the low-velocity zone, but the existence of even more deeply seated heterogeneity has not been excluded. In the more stable continental regions, Phanerozoic platforms (category P) and areas of exposed Precambrian rocks (category S) are distinguished by the data; the former has lower average shear velocities in region B. This fact is important for theories of epierogenesis. Evidently, the large areas of persistent upwarping—Suess's shields—have more mature root zones than do areas that have accepted Phanerozoic cover. A more detailed explanation requires a better theory of continental deep structure, however, and such theories are only now taking shape (58).

The constraints on small- to intermediate-scale (<3000 km) inhomogeneities within the oceanic upper mantle are less good, primarily because the oceans lack seismic stations, but preliminary evidence suggests their existence. Strong azimuthal variations in shear wave travel times have been documented around the Hawaiian Islands (59, 60). In addition, differential travel times between various multiple ScS phase pairs are consistently less for paths from the Kuril–Kamchatka Arc to Oahu than for other paths in the western Pacific (unpublished data); these paths sample the anomalously high topography of the northwest Pacific, including the Hawaiian Swell. Our observations in the western Pacific also show considerable scatter, amounting to several seconds in one-way travel time, which indicates the existence of heterogeneities with scale lengths of ≈1000 km. At present, however, we do not know if these variations are localized in region B or if they are distributed in other mantle layers.

Much better documented are the heterogeneities associated with descending lithospheric slabs. In the well-studied Benioff zones of the western Pacific, the travel times and amplitudes of body waves confirm the model for plate subduction advanced by Isacks *et al.* (6): i.e., an ≈100-km-thick slab penetrating an upper mantle which has lower velocities and higher specific attenuation (6, 61–68). Detailed velocity and attenuation models have been proposed for Japan by Sacks and his coworkers (50, 66, 68); they estimate that the velocity contrasts across the slab's upper boundary in region B are about 5 ± 1% for compressional waves and 7 ± 2% for shear waves, generally consistent with other estimates (e.g., ref. 62). In South America, on the other hand, the descending slab evidently interacts with a thick, advancing, continental tectosphere, and the structure is more complex (50, 66, 68, 69).

Region C Heterogeneity. Velocity anomalies associated with descending slabs have been shown to extend at least as deeply as the Benioff zone seismicity and therefore into region C (62, 64, 70, 71). The velocity contrasts between the slab and surrounding mantle in some deep-focus zones appear to be comparable to those at shallower depths (70, 71), although the data are not unanimous on this point (72).

Aside from Benioff zones, very little evidence has been put forth for lateral variations which can be specifically assigned to region C. Some workers, quoted previously, advocate the extension of continent–ocean heterogeneity into region C, but their arguments have not gained wide acceptance.

If large-scale region C heterogeneities do exist, they may be most obviously expressed as regional variations in the depths of the phase transitions bounding or internal to this zone. A number of regional studies have produced velocity structures of the upper mantle, and these indeed show variations (±25 km) in the depths of discontinuities. There are substantial trade-offs between a discontinuity's depth and the velocity structure above it, however. Given the large variability of region B velocities, any inferences must be made with considerable caution because few studies have explored these trade-offs in detail. A notable exception is the recent work by England *et al.* (73) who argue plausibly for significant differences in the velocity structures of western Europe and the Russian platform extending to 500 km in depth.

Region D Heterogeneity. Bullen's region D—the lower mantle or mesosphere—was divided by him into two layers, D′ and D″, on the basis of a decrease in the compressional velocity gradient about 200 km above the core–mantle boundary (Fig. 1; ref. 15). Until 10 years ago, region D′, comprising the bulk of the lower mantle, was regarded as a relatively homogeneous layer, both radially and laterally (15, 74). The first clear indications of widespread heterogeneity came from the detailed analysis of P-wave arrival angles, facilitated by the advent of large-aperture seismic arrays (16, 75, 76). Evidence for inhomogeneity has grown steadily since then, although the models are still quite primitive and qualitative.

The effects of lower mantle heterogeneity on traditional seismic data are largely obscured by the relatively strong velocity and attenuation variations in the crust and upper mantle. To investigate deep variations, experiments must be designed to reduce this interference. One successful technique has been to use the difference between the travel times of core-reflected (PcP or ScS) and direct (P or S) body waves with similar upper mantle paths. Hales and Roberts (77) demonstrated that ScS-S differential travel times show anomalous scatter not easily attributed to upper mantle structure. Subsequent studies of data from very deep earthquakes have confirmed that this scatter is caused by heterogeneities residing in region D (12). As illustrated in Fig. 6, ScS-S residuals from deep-focus events fluctuate by 5 s or more throughout the distance range of 30–80°.

It was first speculated that the inhomogeneities implied by these fluctuations might lie in the vicinity of the core–mantle boundary (77, 78), but further examination reveals that at least part, and perhaps most, of the scatter results from near-source heterogeneities. In particular, material characterized by anomalously high velocities appears to underlie deep earthquake zones in both the eastern and western Pacific (70, 79, 80). The results strongly suggest that, in some regions of rapid plate subduction, descending slabs penetrate the mantle to depths exceeding 800 km—that is, below the seismicity cutoff and into the mesosphere (12, 70). If this hypothesis is correct, then material is being exchanged between the asthenosphere and the mesosphere, at least locally.

The extension of subduction zone anomalies into the lower mantle has also been inferred from anomalies in P-wave arrival angles from Benioff-zone earthquakes (76, 81–83), although the relationship of these anomalies to the subduction process is less clear. When plotted as "mislocation vectors" (the difference between an event's actual location and its apparent location as seen by a seismic array), these data display a geographic coherence that implies near-source heterogeneity; namely, changes in the patterns of mislocation vectors often occur at changes in subduction zone geometry. The fact that deep events show this behavior argues for variations at or below 700 km in depth. The nature of this heterogeneity has not been precisely quantified, because the inverse problem for mislocation vectors is not well understood, but Powell (83) has attempted to model some aspects of the data. As she has demonstrated, the data evidently require variations beneath the seismic zones with horizontal scale lengths of 1000 km or more. In particular, simple slab models cannot explain all of the observations, although deep slab penetration may be responsible for certain features such as the splitting of mislocation vectors observed at the Norwegian Seismic Array for events in the Middle America Trench (82).

The evidence for inhomogeneities at deeper levels within region D′ is equally strong. Julian and Sengupta (84) have observed that the scatter in P-wave travel times from deep-focus events increases substantially beyond 70°, implying a greater

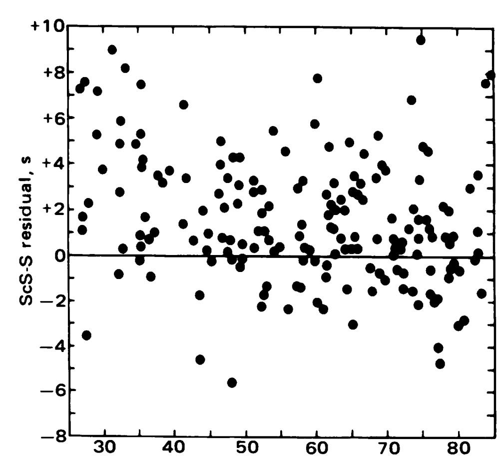

FIG. 6. ScS-S differential travel times from deep-focus earthquakes as a function of epicentral distance. Residuals are observed times minus times computed from Jeffreys–Bullen tables (38), corrected for source depth. Data were collected from the long-period instruments of the WWSSN (78) and show a large scatter attributed to region D heterogeneity (12).

Table 1. Summary of characteristic horizontal scale lengths of wave-speed heterogeneity observed in silicate layers of Earth

Shell	Bullen region	Microscale (<30 km)	Small-scale (30–300 km)	Mesoscale (300–3000 km)	Large-scale (>3000 km)	Description and refs.
Lithosphere	A	•	•	•	•	Crustal heterogeneity
	B	•	•	•	•	Subcrustal lithospheric heterogeneity (19–30, 34)
Asthenosphere			•	•	•	Subduction zone anomalies (6, 50, 61–69); continental roots (12, 31, 33, 34, 37, 46–59); thermal decay (20, 36, 37, 40–42)
	C		•	•		Subduction zone anomalies (62, 64, 70–72); transition zone topography (73)
Mesosphere	D′		•	•		Subduction zone anomalies (12, 70, 76, 79–83)
				•	•	Deep-mantle P-wave anomalies (84, 85)
	D″	•	•	•	•	Basal heterogeneity (78, 84–95)

lateral variability in the mantle below a depth of 2000 km. They estimated that this heterogeneity is characterized by horizontal scale lengths of approximately 1000 km and velocity fluctuations of 1% or more. A much larger set of P-wave times (nearly 700,000) compiled by the International Seismological Centre has been analysed by Dziewonski *et al.* (85), who inverted the data for the lowest order ($l \leq 3$) coefficients in a spherical harmonic representation of deep-mantle velocity variations. These authors resolved large-scale features below 1500 km in depth and concluded that the perturbation amplitudes increase near the base of the mantle, in agreement with Julian and Sengupta's findings for smaller-scale heterogeneity. Most interestingly, they obtained a significant negative correlation between the satellite-derived gravity field and the gravity anomalies computed by assuming isochemical proportionality between velocity and density anomalies. The implications of this important finding are not fully clear, but it appears to be at odds with a simple model of local, convectively induced temperature variations.

Various techniques have demonstrated the existence of significant lateral structures in region D″ with a wide spectrum of horizontal scales, supporting the notion that the lowermost mantle is more heterogeneous than the region above it. The observational techniques have generally made use of the special properties of waves propagating tangentially or nearly tangentially to the core–mantle boundary. For example, Alexander and Phinney (86) found that the spectral characteristics of P waves diffracted along this discontinuity are geographically variable, and they inferred large-scale inhomogeneities in region D″. In contrast, heterogeneities on a much finer scale are implied by Haddon's (87) hypothesis that certain peculiar high-frequency waves precursory to the core phase P'_{DF} are energy scattered at or near the core–mantle boundary. Detailed studies have generally confirmed Haddon's idea (88–92), and the horizontal scale lengths of the scatterers has been estimated at 10–50 km (89, 92). The data are less specific on the exact location of the heterogeneity; they can be explained by either "lumps" in region D″, with velocity variations of a few percent, or "bumps" on the core–mantle interface, with amplitudes of a few hundred meters. Recently, however, Chang and Cleary (93) have observed precursors up to 65 s before the PKKP phase at distances near 60°, which they show are most simply explained by bumps on the interface. Sacks and his co-workers (94, 95) have examined the amplitudes of the phase P'_{AB}, which intersects the core interface at an oblique angle, relative to P'_{DF}, which is almost normally incident. From the geographic coherence of these ratios, they argue for heterogeneity on a somewhat larger scale ($\approx$150 km) and speculate that it may be a manifestation of convective activity in region D″.

QUESTIONS OF STRUCTURAL INTERPRETATION

The salient observations of wave-speed lateral heterogeneity are summarized in Table 1, where the horizontal dimensions characterizing the heterogeneity spectrum are indicated for each of the major layers.¶ The table is certainly not complete: observed features not yet assignable to specific layers have been omitted (e.g., the mesoscale anomalies of the western Pacific evident in the multiple ScS travel times), and many more must surely lie undiscovered. But even in this early stage of structural investigation, we can begin the geological interpretation of lateral variations.

To phrase our questions, it is convenient to define some specific terms for the important types of heterogeneity. *Compositional heterogeneities* are those attributable to spatial variations in chemical composition, including the variations in minor elements such as volatiles. Field observations demonstrate that crustal inhomogeneities are primarily of this type and that compositional heterogeneities extend at least into the lithospheric mantle. *Aeolotropic heterogeneities* are those associated with spatial variations in anisotropic properties. Mesoscale and large-scale aeolotropic heterogeneities have been mapped in the oceanic lithosphere (19–21), and, according to Fuchs (22), some of the small-scale and microscale heterogeneities of the lithosphere might be aeolotropic as well. *Thermobaric heterogeneities* are those caused by the spatial variations in temperature and pressure, including any variations due to isochemical phase changes and electronic transitions. The wave-speed variations in the lithosphere induced by conductive cooling are thermobaric heterogeneities. Lithospheric heterogeneity is thus a mixture of all three types: compositional, aeolotropic, and thermobaric.

What properties characterize the deeper variations? At this time, the answers are speculative; the models are hypothetical. The problem of continental deep structure, for example, is often discussed in terms of purely thermobaric heterogeneity. According to the thermal boundary layer hypothesis, the subcontinental upper mantle is strongly heated during major orogenesis and subsequently cools by the conduction of heat to the surface; the cratons are explained as areas that have been cooling for a very long time and where the thermal boundary layer has grown to extreme thickness. The time scales are about right to explain the basic seismic observations, but one difficulty with this model is the apparent conflict between the predicted isostatic behavior of the cratons and the observations of epeirogenesis: stable continental areas simply do not show the ex-

¶ In discussing the heterogeneity spectrum relevant to seismology, I shall use the terms "microscale," "small-scale," "mesoscale," and "large-scale" to designate horizontal dimensions of order 10^1, 10^2, 10^3, and 10^4 km, respectively.

tended history of subsidence and crustal thickening required by the model. Indeed, the highest region-B shear velocities, and presumably the lowest temperatures, are found beneath the shields, whose recent history is one of uplift and erosion. Furthermore, a thick, chemically homogeneous, thermal boundary layer is probably convectively unstable (49); it would be quickly disrupted and eventually destroyed rather than persist through the eons as a stable continental root. One is forced to conclude that continental deep structure cannot be purely thermobaric unless it is maintained by advection, a possible but unattractive alternative. In fact, continental deep structure is likely to involve compositional as well as thermobaric heterogeneity (49, 58). The specific model that I favor incorporates a type of heterogeneity best described as *isopycnic,* because it postulates that the density effects of thermal and compositional variations in the sublithospheric continental root zones are roughly equal in magnitude but opposite in sign. Isopycnic heterogeneities capable of surviving for long periods could be generated by the consolidation beneath the continents of mantle material previously depleted in basaltic constituents, an idea that receives some support from studies of kimberlite xenoliths (58, 96). The hypothesis implies that continental roots are part of the tectosphere.

Heterogeneities that are likely to be primarily thermobaric are the subduction zone anomalies, the seismic expressions of detached and sinking thermal boundary layers. The question here is: How deeply extends the circulation they imply? If one accepts the evidence for high-velocity subduction zone anomalies in the upper parts of region D, then it is difficult to postulate no mass exchange between the asthenosphere and the mesosphere. On the other hand, the mass flux across the 670-km discontinuity might still be small compared to the total mass flux involved in the plate tectonic circulation. Within the next decade or so, structural seismology should provide the constraints on the flow geometry necessary to resolve these and other problems of mantle dynamics. Could it be, for example, that the mesoscale western Pacific anomalies are thermobaric expressions of flows confined within the asthenosphere?

Even more challenging are the deep-mantle anomalies and basal (region D″) heterogeneities of Table 1. Of these features very little is known, but we can engage in some fanciful speculations. Significant mass flux across the core–mantle interface is presumably inhibited by its large density contrast ($\approx$4300 kg/m^3), which substantially exceeds that at the Earth's surface. If the lower mantle is convecting, due in part to heat flux from the core, then there will be a thermal boundary layer at its base, probably occupying a significant portion of region D″ (97). Basal heterogeneities could thus be thermobaric variations within this boundary layer, and at least some of the anomalies in region D′ could be caused by its detachment and rise through the mantle. We would expect anomalies of this sort to be strongest near the boundary layer, which could explain the apparent increase in heterogeneity below about 2000 km in depth.

The analogy with upper mantle heterogeneity is obvious and attractive, and perhaps it can be extended even further. At the surface we find not only a thermal boundary layer but also a chemical boundary layer—the crust—inhomogeneous on many scales, including microscale variations that scatter seismic waves. At the base of the mantle we again find a layer inhomogeneous on many scales, where scattering by microscale variations is also observed. Could these variations indicate the existence of another chemical boundary layer at the Earth's other major chemical transition? We might postulate a solid slag on the core's liquid iron surface too dense to be easily transported out of region D″ by convective action, just as the continents remain on mantle's outer surface. Such a crust could provide isostatic support for any subtle topography on the core–mantle interface (a more dynamically feasible scenario than uncompensated topography). Mountain ranges could be piled up and huge rafts pushed about, perhaps in a tectonics not totally strange to the surface geologist.

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